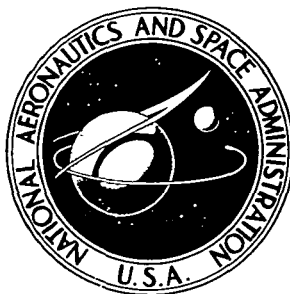


**NASA TECHNICAL  
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**NASA TM X-3327**

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**ABSOLUTE CALIBRATION OF  
A HYDROGEN DISCHARGE LAMP  
IN THE VACUUM ULTRAVIOLET**

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|--|---|-------------------------------|-----------------------------|---|--|
| 1. Report No.<br><b>NASA TM X-3327</b>   |   | 2. Government Accession No.   |                             | 3. Recipient's Catalog No.  |  |
| 4. Title and Subtitle<br><b>ABSOLUTE CALIBRATION OF A HYDROGEN DIS-<br/>CHARGE LAMP IN THE VACUUM ULTRAVIOLET</b>  |   |                               |                             | 5. Report Date<br><b>December 1975</b>  |  |
|  |   |                               |                             | 6. Performing Organization Code   |  |
| 7. Author(s)<br><b>John E. Nealy</b>   |   |                               |                             | 8. Performing Organization Report No.<br><b>L-10699</b>   |  |
| 9. Performing Organization Name and Address<br><br><b>NASA Langley Research Center<br/>Hampton, Va. 23665</b>  |   |                               |                             | 10. Work Unit No.<br><b>506-26-20-01</b>  |  |
|  |   |                               |                             | 11. Contract or Grant No.   |  |
| 12. Sponsoring Agency Name and Address<br><br><b>National Aeronautics and Space Administration<br/>Washington, D.C. 20546</b>  |   |                               |                             | 13. Type of Report and Period Covered<br><b>Technical Memorandum</b>                                |  |
|  |   |                               |                             | 14. Sponsoring Agency Code  |  |
| 15. Supplementary Notes<br><br><b>Appendix entitled "Operation Procedure and Listing of Instrumentation" by<br/>William K. Goad, Langley Research Center.</b>  |   |                               |                             |   |  |
| 16. Abstract<br><br><p>A low-pressure hydrogen discharge lamp has been calibrated for radiant intensity in the vacuum ultraviolet spectral region on an absolute basis and has been employed as a laboratory standard source in spectrograph calibrations. This calibration was accomplished through the use of a standard photodiode detector obtained from the National Bureau of Standards together with onsite measurements of spectral properties of optical components used. The stability of the light source for use in the calibration of vacuum ultraviolet spectrographs and optical systems has been investigated and found to be amenable to laboratory applications. The lamp was studied for a range of operating parameters; the results indicate that with appropriate peripheral instrumentation, the light source can be used as a secondary laboratory standard source when operated under preset controlled conditions. Absolute intensity measurements were recorded for the wavelengths 127.7, 158.0, 177.5, and 195.0 nm for a time period of over 1 month, and the measurements were found to be repeatable to within 11 percent.</p> |   |                               |                             |   |  |
| 17. Key Words (Suggested by Author(s))<br><br><b>Vacuum ultraviolet spectroscopy<br/>Spectrograph calibration</b>  |   |                               |                             | 18. Distribution Statement<br><br><b>Unclassified — Unlimited</b><br><br><b>Subject Category 14</b> |  |
| 19. Security Classif. (of this report)<br><b>Unclassified</b>  | 20. Security Classif. (of this page)<br><b>Unclassified</b> | 21. No. of Pages<br><b>31</b> | 22. Price*<br><b>\$3.75</b> |   |  |

# ABSOLUTE CALIBRATION OF A HYDROGEN DISCHARGE LAMP IN THE VACUUM ULTRAVIOLET

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## SUMMARY

A low-pressure hydrogen discharge lamp has been calibrated for radiant intensity in the vacuum ultraviolet spectral region on an absolute basis and has been employed as a laboratory standard source in spectrograph calibrations. This calibration was accomplished through the use of a standard photodiode detector obtained from the National Bureau of Standards together with onsite measurements of spectral properties of optical components used. The stability of the light source for use in the calibration of vacuum ultraviolet spectrographs and optical systems has been investigated and found to be amenable to laboratory applications. The lamp was studied for a range of operating parameters; the results indicate that with appropriate peripheral instrumentation, the light source can be used as a secondary laboratory standard source when operated under preset controlled conditions. Absolute intensity measurements were recorded for the wavelengths 127.7, 158.0, 177.5, and 195.0 nm for a time period of over 1 month, and the measurements were found to be repeatable to within 11 percent.

## INTRODUCTION

Considerable interest in quantitative spectroscopy in the vacuum ultraviolet spectral region ( $\approx 50$  to 200 nm) has developed in the last few years. A growing number of applications for vacuum ultraviolet research projects is attributed primarily to the large amounts of energy contained in this spectral region in many high-temperature phenomena. (See, for example, ref. 1.) In addition, atomic and molecular absorption coefficients at these short wavelengths are high. Such high coefficients can lead to important energy transfer effects, *which could determine the energy balance existing in the upper atmospheres of planets. These* effects are also significant in astrophysical problems (such as steady-state stellar structure), high-temperature electric arcs, and regions behind bow shock waves of high-speed planetary probes. The study of radiation behind hypervelocity shock waves in representative atmospheres of Venus and the outer planets stimulated the calibration of a light source at the Langley Research Center. This paper describes the calibration of such a light source.

As is well recognized, quantitative spectroscopy in this spectral region abounds in technical difficulties in such areas as controlled ultraviolet light sources, optical components,

detection apparatus, and analysis. An excellent description of many of the various problem areas and approaches to meeting these difficulties may be found in reference 2. This reference discusses two methods for performing absolute-intensity calibrations: (1) the use of detectors having known spectral response, and/or (2) the use of a standard source of radiation for which the spectral intensity has been determined.

At the time that quantitative vacuum ultraviolet intensity measurements were initiated in the arc-driven shock tube at the Langley Research Center, there were no suitable or convenient standard sources known to be available in the spectral range of interest. Although the electron synchrotron (refs. 3 and 4) and arc-generated plasmas (refs. 5 and 6) have recently been established as radiometric standard sources, they are not readily available for laboratory applications such as shock-tube studies. On the other hand, calibrated photodiode detectors were available and a study of the transmission of a four-channel spectrometer was performed and reported in reference 7. This method of calibration proved to be laborious and lacking in versatility. Therefore, a more practical and improved calibration technique was sought.

During the past decade, a general purpose, commercially available ultraviolet light source of a capillary discharge type has been in use for research in the Langley shock tube. Such qualitative applications as wavelength determinations, transmission checks, and detector response evaluations disclosed the excellent reliability and stability of this light source. Thus, the possibility of its use as an absolute calibration source was considered, and a research investigation in the summer of 1974 was granted for such a feasibility study. Under this grant, an initial determination of various parameters affecting the lamp operation and intensity was made.<sup>1</sup> In the continuation of this effort, solutions to various problems encountered in the grant study were pursued and studied in more detail.

This paper presents the results of an extensive survey of the lamp stability and operation, together with its absolute calibration and use as a laboratory standard. The primary advantage of having such a calibrated source rather than calibrated detectors is that the calibrated source may be employed in the determination of the absolute spectral sensitivity of entire optical systems used in direct applications. A calibrated source eliminates the necessity of individual calibration of each component of the detection apparatus. As stable and repeatable ultraviolet light sources become readily available and convenient to use, a source calibration technique such as the one described here should provide more rapid and accurate pursuit of many quantitative vacuum ultraviolet research projects. The monitoring and readout equipment associated with this light source is discussed in the appendix, prepared by William K. Goad of Langley Research Center.

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<sup>1</sup>Work done by F. W. Paul, Research and Investigation of a Source of Vacuum Ultraviolet Radiation for Use in the Calibration of Spectrometers (Chesapeake College; NASA Grant NSG-1066).

## SYMBOLS

|                    |   |
|--------------------|---|
| A                  | area, $m^2$   |
| c                  | speed of light, 299.8 Mm/s                            |
| h                  | Planck constant, $6.626 \times 10^{-34}$ J-s          |
| $I_\lambda$        | spectral intensity, $W/cm^2\text{-}\mu m\text{-sr}$   |
| $i_\lambda$        | signal current, A                                     |
| K                  | constant in equation (1), $6.24 \times 10^{18}$       |
| $Q_\lambda$        | quantum efficiency                                    |
| $S_\lambda$        | radiant sensitivity, W/A                              |
| $\epsilon_\lambda$ | optical efficiency (reflectance, transmittance, etc.) |
| $\eta_\lambda$     | energy conversion efficiency of sodium salicylate     |
| $\lambda$          | wavelength, nm  |
| $\Omega$           | solid angle, sr                                       |

## DESCRIPTION OF INSTRUMENTATION

In general, high-voltage discharges in low-pressure gases are not noted for producing stable and reproducible radiant intensities. However, after noting the repeatability of the hydrogen spectrum produced by a commercially available light source in the region between 100 and 200 nm, the use of that light source as a laboratory standard was considered. The primary concern for such application was to improve the repeatability of the spectral characteristics of the lamp. The variant parameters in the study of lamp performance were gas pressure, flow rate, and operating voltage and current for the discharge. Provision was made for accurate monitoring and readout instrumentation associated with the measurement of these parameters and their influence on lamp output. Other long term factors are expected to have an influence on lamp characteristics: deterioration of electrode material and the gradual normal attrition of lamp parts exposed to the electric discharge. In addition to the basic

lamp and its controlling and monitoring instrumentation, some other auxiliary equipment is necessary to establish and maintain this standard source. Briefly, this equipment and its purposes are: (1) a spectrally calibrated ultraviolet detector whose signals may be related to the absolute intensity of radiation received; (2) a separate monochromator and vacuum reflectance chamber for measuring spectrograph grating efficiency; and (3) a vacuum spectrograph (preferably single-surface) to be used in the final lamp calibration.

The basic lamp is of a type developed at the Air Force Cambridge Research Center by Dr. H. Hinteregger. (See ref. 8.) A cross-section diagram is shown in figure 1. The discharge takes place between an air-cooled cathode and a water-cooled anode. A water-cooled quartz capillary separates the electrodes. The capillary has internal dimensions of 8.6 cm in length and 0.5 cm in diameter. In order to maintain acceptable gas purity in the discharge region, a steady flow is established by regulating valves between the gas supply and the vacuum pump attached to the lamp. Although a number of gases or gas mixtures could be used, only pure (99.999 percent) hydrogen was considered for this investigation. This choice was determined primarily because of the substantial radiation from the discharge in hydrogen over the entire 100 to 200 nm range. Also, hydrogen is relatively inexpensive, readily available in high purity grades, and appears to have no deleterious effect on optical surfaces inside the vacuum spectrograph when the lamp is operated in a windowless mode. (Noble gases would also be candidates for use in this type of lamp; the spectral-emission characteristics of these gases are discussed in detail in refs. 9 and 10.)

Recent far-ultraviolet technology has provided photodiode detectors which may be used as primary calibration devices. A general description of these detectors and a demonstration of their use as a standard are found in reference 11. The spectral quantum efficiency of the photodiode used in the present lamp calibration was determined at the National Bureau of Standards (NBS) for wavelengths between 116.4 and 253.7 nm. The probable error of this calibration is quoted to be 6 percent between 116.4 and 200 nm. Figure 2 shows the NBS-determined quantum efficiency  $Q_\lambda$  and the converted radiant sensitivity  $S_\lambda$  of the detector as determined from the relationship

$$S_\lambda = \frac{Khc}{\lambda Q_\lambda} \quad (1)$$

where  $K$  is the number of electrons per sec equivalent to 1 ampere ( $6.24 \times 10^{18}$ ).

The photodiode obtained from NBS has an opaque cesium telluride cathode and a magnesium fluoride window and is operated with the anode voltage at 60.0 volts relative to the cathode. As discussed in reference 11, the quantum efficiency is uniform over practically the entire cathode area for all wavelengths. In the present investigation, only a small portion of the cathode area ( $\approx 0.1$  by  $0.5$  cm) was irradiated.

To establish the intensity of a light source by using a standard detector, the spectral properties of all optical components used between the detector and the source must be accurately determined. With the present technique, the only such measurement necessary was of the efficiency of a single concave grating. For this purpose, a special vacuum chamber designed by W. M. Houghton of Langley Research Center was employed. A diagram of this reflectance chamber is shown in figure 3. In addition to the vacuum pumping system needed to evacuate the chamber to a pressure on the order of  $1 \text{ mN/m}^2$ , a general purpose ultraviolet light source providing the necessary wavelengths and a vacuum monochromator are required. The monochromator (in this case a Seya monochromator) is used to introduce collimated light of desired wavelengths into the chamber. Inside the chamber is a sodium salicylate coated photomultiplier tube which may be positioned at two different locations. In the first position, the relative intensity of the monochromatic beam is measured as it enters the chamber. By rotation of an external handle, the photomultiplier is placed in its second position. There the light-beam intensity is determined after it has reflected from an optical component whose spectral reflectance is being evaluated. Provision is also made for rotating the optical element under test externally. A window holder is located at the entrance aperture of the chamber. When window transmission is to be measured, the window may be inserted into the beam. Measurements of this type are made with the photomultiplier in its first position. The window holder is also used for sorting spectral orders.

The grating efficiency is defined as the ratio of the detector signal resulting from reflection or dispersion to the signal of the incident monochromatic beam. Since spectral reflectance of a mirror or grating in this wavelength range can undergo relatively sudden changes caused by surface contamination, this measurement must be made at regular time intervals. The particular grating used in this study has a 1-m focal length, 1200 lines/mm, and a blaze wavelength and angle of 120 nm and  $4^{\circ}8'$ , respectively.

Figure 4 shows the results of efficiency measurements for the zero and first order of this grating. The zero-order measurements (specular reflectance) exhibit a typical monotonic increase in efficiency through the vacuum ultraviolet wavelength, while the first-order results show an expected peak efficiency near the blaze wavelength. In a concurrent shock-tube study of radiation behind strong shock waves in carbon dioxide, a carbon line (127.7 nm) and the carbon monoxide fourth positive band system (158.0, 177.5, and 195.0 nm) were being investigated. These particular wavelengths dictated where the lamp calibration was performed. After the initial first-order grating-efficiency measurements were performed under the grant study at closely spaced wavelength intervals, the four wavelengths mentioned earlier were used to monitor the condition of the 1-m grating. These check points were made over a 1-year period, and, in no instance, was any indication of grating deterioration observed.

## CALIBRATION PROCEDURE

### Description of Setup and Operation

The calibration of the lamp was performed with the arrangement depicted schematically in figure 5. Gas pressure and flow rate for the lamp were carefully regulated and monitored by transducers with the associated amplifiers and digital readout equipment. (See appendix.) A photograph of the setup is shown in figure 6. The 1-m spectrograph is provided with a pumping system capable of producing an ultimate vacuum of  $0.1 \text{ mN/m}^2$ . However, when the lamp is in windowless operation, the pressure inside the spectrograph is somewhat higher as a result of leakage of hydrogen through the entrance slit, and is maintained at about  $1 \text{ mN/m}^2$ . The operating voltage for the calibrated photodetector at the exit slit is provided by a regulated dc power supply. Since the signal currents are very small ( $\approx 10 \text{ pA}$ ) and susceptible to random noise, a picoammeter is used in conjunction with an integrating digital voltmeter and a reset timer to record output signals. Pertinent specifications for this equipment and a detailed procedural description are presented in the appendix.

The efficiency of a concave grating has been shown to vary by 50 percent or more at different spatial locations on the grating surface (ref. 12). To minimize this effect, a mask obscuring most of the ruled surface was introduced into the calibration system. This mask was placed immediately in front of the grating and its open rectangular area of 17 by 23 mm was centered on the 56- by 96-mm ruled area. Of course, a sacrifice in f-number is made; however, the use of a portion of the grating for which the efficiency is practically uniform makes this sacrifice worthwhile when sufficient source intensity is available. In order to verify that the unmasked portion of the grating had acceptable uniformity, an exposure was made on vacuum ultraviolet sensitive film. The film was placed away from the grating focal plane in order to record an image of the grating surface. Subsequent microdensitometer analysis indicated that the variation in dispersed light intensity across the exposed portion of the grating was less than 5 percent.

### Sources of Major Uncertainties

The most severe effect on stability is caused by variation in entrance slit area. The rapidly changing transmission properties of ultraviolet windows prohibit the operation of the lamp with a magnesium fluoride or lithium fluoride window. For lamp operation in a windowless condition, an accurate setting of the entrance slit width between 20 and  $50 \text{ }\mu\text{m}$  was required. Poor repeatability occurring with a spring-actuated adjustable slit led to the use of a commercial fixed-slit assembly. After a period of use, microscopic examination of the fixed slit revealed that changes were occurring to the slit geometry. Long term operation of the lamp caused a coating of aluminum oxide within the ionization region, and aluminum particulate buildup was observed on the edges of the entrance slit. Scanning with an electron



microscope revealed sufficient aluminum particulates blocking the open slit area to result in a 50-percent error in measurements. In addition, the cold side or spectrometer side of the slit revealed a large buildup of silicon particulates (presumably from the quartz capillary). These silicon ablator products did not contribute to a change in the area of the slit opening, and silicon particulate migration at this time is believed to extend no further into the spectrometer than the immediate vicinity of the entrance slit. Area changes in the entrance slit are most noticeable through changes in lamp stability or repeatability, and have been apparent only after more than 100 hours of lamp operation with the present system. When blockage is detected, the system is disassembled and cleaned, and the slit width is reset.

These findings concerning variation in slit geometry have led to the use of a rotary fixed-slit assembly of four slits. By setting each slit as accurately as possible to the same width and using one for reference purposes only, a better check on accumulated blockage of any of the three remaining slits is obtained.

The intensity of the many-line hydrogen spectrum shows considerable variation with wavelength. Accurate setting of the desired wavelength is essential to good repeatability. Observations on the present system show that a 0.1-nm deviation in wavelength setting at 122.7 nm and 158 nm results in intensity measurement deviations of 4 and 8 percent, respectively. As previously mentioned, lamp operation in a contaminated state can also result in errors as high as 40 percent. These problem areas of a procedural nature can be avoided when their existence and nature are established.

Two other problems, which are not readily controllable, are associated with the lamp operation; these are coating and corrosion of the electrodes. Ionization between the aluminum electrodes of the lamp causes a gradual coating of aluminum oxide on the conducting surfaces. After approximately 200 hours of operation, it is not possible to ionize the gas because of the dielectric effects of the coating that are evidenced over a period of time by the steady increase of voltage required for ionization. A lamp using stainless steel electrodes is currently being tested in an effort to alleviate this problem. Water cooling of the aluminum anode resulted in corrosive effects over a longer time period; such corrosion led to water and vacuum leaks. This problem is also expected to be alleviated by the change in electrode material. Corrosion and dielectric coating problems are both relatively long term. However, both problems can be corrected by disassembling, cleaning, and repairing of the electrodes and capillary.

## RESULTS AND DISCUSSION

Gas flow rate and, more important, gas pressure must be accurately controlled if the lamp is to be operated repeatably. Furthermore, it is desirable to ascertain the variation of lamp intensity as these parameters are changed; so that evaluations of required instrumentation

accuracy and of effects of small deviations from preset values can be made. In this study, lamp-intensity data at the wavelengths 127.7, 158.0, 177.5, and 195.0 nm have been recorded for a range of pressures and flow rates. A map of the data points taken at these various pressures and hydrogen flow rates is given in figure 7. The region over which the lamp operated was determined by the maximum allowable internal spectrograph pressure and the vacuum pump-metering valve combination on the lamp. Previous vacuum spectrograph operation has demonstrated that internal spectrograph pressure should not exceed  $0.01 \text{ N/m}^2$  while optics are being illuminated with ultraviolet radiation. In a windowless operation, only certain pressures are attainable at specified flow rates; these pressures and the corresponding flow rates of figure 7 apply to the present system only. Operation of the lamp with a different spectrograph or valving arrangement would result in a different pressure and flow-rate map. For the range of conditions shown in figure 7, the variation of detector signal was found to have a distinct relationship with lamp pressure; however, the signal remained essentially constant with flow rate for values less than  $15 \text{ std cm}^3/\text{min}$ .

Figure 8 shows detector output as a function of internal lamp pressure, and at each pressure the vertical bar shows the range of signals recorded for all flow rates sampled at that pressure. The detector used to obtain the results of figure 8 was an end-on photomultiplier tube with sodium salicylate phosphor and was operated at 800 volts dc. At each wavelength for which these observations were made, the lamp intensity was relatively insensitive to pressure variations around a value of  $133 \text{ N/m}^2$ ; hence, this pressure has been chosen as a standard operating condition of the lamp together with a flow rate of  $5 \text{ std cm}^3/\text{min}$ . (These conditions are easily obtained with the present valve, pump, and entrance slit combination.)

The current-regulated dc power supply for the discharge lamp was used to determine how the lamp intensity was affected by changes in discharge current. The power supply exhibited more than adequate stability characteristics. (That is, no noticeable current shift for lamp operation times up to 1 hour was observed.) Photomultiplier output is plotted as a function of discharge lamp current in figure 9. It can be seen that relative intensity varies only about 0.16 percent per mA over a range of currents between 125 and 240 mA. Thus, the current is easily controlled and is a negligible factor in establishing overall lamp performance as a standard source. The normal preset operating current for the present lamp calibrations was chosen to be 160 mA. This value (slightly lower than median) provided adequate intensity and was believed to be less taxing on the long term operation of the lamp than a higher current.

Upon the establishment of the desired operating parameters for the light source and the determination of the appropriate grating efficiency, absolute calibration of the lamp was performed. With the instrumentation setup shown in figure 5, the signals of the NBS photodiode were recorded for the four wavelengths previously mentioned. Individual intensity measurements were made over 100-second time intervals, and the averaged signal currents in picoamperes were

determined for each wavelength. These results, summarized in table I, were obtained on various days over a total period of about  $1\frac{1}{2}$  months. The currents recorded in table I were measured under the established "normal" operating conditions:

|  |                              |
|--|------------------------------|
| Lamp internal pressure, N/m <sup>2</sup> . . . . . | 133.3 ± 0.6                  |
| Hydrogen flow rate, cm <sup>3</sup> /min . . . . . | 5.00 ± 0.05                  |
| Discharge current, mA . . . . .                    | 160 ± 2                      |
| Photodiode voltage, V . . . . .                    | 60.00 ± 0.05                 |
| Spectrograph entrance slit . . . . .               | 38 μm by 0.503 mm            |
| Spectrograph exit band pass, nm . . . . .          | 0.83 (exit slit width, 1 mm) |

The deviations shown for these quantities are indicative of the maximum observed drift in pre-set values occurring during a single set of measurements, normally a period of about 1/2 hour.

The absolute spectral intensity of the light source  $I_\lambda$  may be determined from the calibrated photodiode signal currents  $i_\lambda$  using the relation

$$I_\lambda = \frac{S_\lambda i_\lambda}{(\Delta\lambda)\epsilon_\lambda A\Omega} \quad (2)$$

In equation (2),  $\epsilon_\lambda$  is the efficiency of the intermediate optical system (in this case a grating),  $A$  is the frontal area of the emitting source (spectrograph entrance slit),  $\Omega$  is the solid angle subtended by the optical system, and  $\Delta\lambda$  is the exit wavelength band pass over which the spectrum is observed. For all the calibration, the following quantities were invariant:

$$\Delta\lambda = 0.83 \pm 0.01 \text{ nm}$$

$$A = 0.000195 \pm 0.000010 \text{ cm}^2$$

$$\Omega = 0.000391 \pm 0.000015 \text{ sr}$$

With  $S_\lambda$  and  $\epsilon_\lambda$  determined from figures 2 and 4, respectively, the conversion from measured signals to normal intensities yields:

| $\lambda$ ,<br>μm | $I_\lambda$ ,<br>W/cm <sup>2</sup> -μm-sr |
|-------------------|---|
| 127.7             | 0.863 ± 0.117                             |
| 158.0             | 1.086 ± 0.146                             |
| 177.5             | 0.0659 ± 0.0078                           |
| 195.0             | 0.495 ± 0.0071                            |

The uncertainties for  $I_\lambda$  given in the preceding table represent the root mean square (rms) error obtained from uncertainties of each of the quantities in equation (2). The total uncertainties for each of the four wavelengths are all under 16 percent.

In addition to these measurements at the four wavelengths of interest, a scan of the spectrum from 100 to 200 nm is presented in figure 10. The scan was performed with the basic setup of figure 5, with the exception of a sodium salicylate photomultiplier tube used in place of the photodiode and a strip chart recorder for final readout. Accompanying the scan, which represents direct output current of the photomultiplier, is a photograph of the spectrum of the discharge in hydrogen. A special vacuum ultraviolet sensitive film of the low gelatin type was used in making the exposure.

The scan of figure 10 is directly related to the spectral intensity of the lamp since it was made under conditions identical to those of the photodiode calibrations. This relation may be determined provided knowledge of the spectral behavior of the sodium salicylate coating is available. Unfortunately, many conflicting measurements of the absolute quantum efficiency of this phosphor have been published. (See, for example, ref. 13.) The salicylate coating for the photomultiplier employed here was prepared in-house according to a procedure similar to that outlined in reference 14. An area of 2 cm<sup>2</sup> directly in front of the photocathode of the tube was masked on the glass envelope prior to deposition. Application of the deposit was made with an artist's air brush using 23 N/cm<sup>2</sup> of high purity nitrogen at a distance of 80 to 100 centimeters. The tube was sprayed with the salicylate and absolute methyl alcohol solution for 30 minutes, then weighed on a balance. Deposits on each tube ranged from 2.5 to 4 mg/cm<sup>2</sup> (5 to 8 mg total weight). Individual coatings were viewed under magnification to examine uniformity.

The absolute quantum efficiency as determined in reference 15 is  $0.94 < Q_\lambda < 1.0$  for  $121.6 < \lambda < 253.7$  nm. For simplicity, a constant value of 0.95 was used for  $Q_\lambda$  in subsequent calculations over the 100- to 200-nm wavelength range. Since the fluorescent radiation of sodium salicylate is centered at a wavelength of 425 nm, the energy conversion efficiency is

$$\eta_\lambda = Q_\lambda \frac{\lambda}{425} \quad (3)$$

Thus, if the coated photomultiplier signal  $i_\lambda$  is divided by the product of  $\eta_\lambda$  and the grating efficiency  $\epsilon_\lambda$ , spectral scans like that of figure 10 may be converted into plots of source relative intensity since

$$I_\lambda \propto \frac{i_\lambda}{\eta_\lambda \epsilon_\lambda} \quad (4)$$

Since the first-order grating efficiency of figure 4(a) is a well-behaved function of wavelength, a polynomial fit was applied to the data of this figure:

$$\epsilon_{\lambda} = 1.946 \times 10^{-10} \lambda^4 + 5.111 \times 10^{-7} \lambda^3 - 2.997 \times 10^{-4} \lambda^2 + 0.05177\lambda - 2.616 \quad (\lambda \text{ in nm}) \quad (5)$$

As a further step, the proportionality factor of equation (4) may be estimated from the monochromatic calibration results, and an absolute scale may be applied to the complete spectrum. Figure 11 shows the results of this procedure, in which equations (3), (4), and (5) were applied to digital data for the  $i_{\lambda}$  obtained from the scan of figure 10. The ordinate scale was determined from the photodiode calibration for the absolute intensity value obtained at 158 nm. Of course, there are a number of uncertainties inherent in this analysis, and an estimate of the degree of uncertainty in the curve of figure 11 is indicated at several wavelengths. The higher discrepancies between figure 11 and the photodiode results at the longer wavelengths quite probably arise primarily from the low signal levels as they appear on the linear scale of the scan (see fig. 10) and from the resultant difficulty in conversion to digital data.

The calibrated lamp was used to determine the response of a 0.5-m four-channel polychromator. This instrument, which was used in a shock-tube study, has three optical surfaces: collimating mirror, plane grating, and focusing mirror. A mask over the collimating mirror set the solid angle of the polychromator at the same value as that used in the lamp calibration. Four coated photomultipliers were placed behind a series of focal plane slits to define the desired wavelengths and band passes. A diagram showing the lamp as used on this spectrograph is given in figure 12. With this arrangement, each channel is calibrated for its response to a given irradiance at the spectrograph entrance slit. After several such measurements, the lamp was replaced on the 1-m spectrograph and its output was again checked with the NBS photodiode. The scatter occurring in the measurements made on the 0.5-m spectrograph was within the probable-error percentages found for the lamp calibrations (less than 12 percent). The present procedure has thus established a satisfactory confidence level for shock-tube intensity measurements made with the polychromator. It should be noted that the lamp has been used on one particular spectrograph, and its application to other optical systems would necessarily require independent validation.

### CONCLUDING REMARKS

A commercially available, low-pressure hydrogen discharge lamp has been calibrated for radiant intensity in the vacuum ultraviolet spectral region on an absolute basis. This calibration

has been accomplished through the use of a standard photodiode detector obtained from National Bureau of Standards together with onsite measurements of the spectral properties of a concave grating. The adequate stability of this light source for use in the calibration of ultraviolet spectrographs and optical systems has been demonstrated. The effects of pressure, gas flow rate, and electrode current on the output intensity of the lamp have been investigated in detail. From the calibration results, it is concluded that with appropriate vacuum spectroscopic equipment, detectors, and monitoring instrumentation, the light source can be used as a convenient secondary laboratory standard. Among the advantages of having a reliable standard source is that the spectral response of entire optical systems may be readily determined, often with geometrical arrangements identical to those for which radiometry studies are to be carried out. This procedure eliminates the necessity for time-consuming individual component calibrations with the associated cumulative uncertainties. The lamp investigation has been observed to be spectrally stable under preset operating conditions. Intensity measurements whose total error is estimated to be within 16 percent were recorded for the wavelengths 127.7, 158.0, 177.5, and 195.0 nm during a time period of over 1 month.

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Hampton, Va. 23665  
December 9, 1975

## APPENDIX

### OPERATING PROCEDURE AND LISTING OF INSTRUMENTATION

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#### Operating Procedure

The appendix discusses operating procedures and instrumentation used in a recent study of the discharge lamp. Systematic procedures were employed to determine the absolute intensity and stability of the lamp and its behavior for variations in gas flow rate, pressure, and power input.

At the beginning of the calibration procedure two steps were established: a decontamination period and a burn-in period. The decontamination period is defined as the pumping time needed to establish the system leak rate at less than  $1.3 \text{ N/m}^2$  per hour. During this time, impurities are effectively removed from the system before the lamp is turned on. A period of 12 hours of evacuation was usually required when the system was initially at atmospheric pressure. For a previously decontaminated and sealed system, only 2 hours of preliminary pumping were needed. This evacuation period is a precautionary measure since a pronounced deterioration of the optical surfaces with time occurs with a contaminated system.

Burning the lamp for two or three 30-minute intervals (referred to here as the burning-in period) before recording data resulted in improved repeatability. The need for the burning-in period was observed while evaluating lamp stability. When the lamp was first turned on, its intensity was consistently low if the system had been out of operation for more than 1 week. After such an idle period, lamp intensities about 40 percent below normal were observed for the wavelength range under investigation. This effect is attributed to impurities migrating to the wall of the water-cooled capillary. Visual observation served as a helpful guide in determining the time required for the burning-in process. Initiating the discharge first results in a light pink glow in the capillary with bands or striations along the discharge column. As the lamp stabilizes, the glow tends toward a more reddish color, and the column becomes more uniform.

The lamp-operating procedure which proves most effective when the system is initially at atmospheric pressure follows.

Performance of grating-efficiency measurements.- This step requires installation of the grating in the reflectance chamber and mounting of the ultraviolet light source at the entrance slit of the Seya spectrograph. Evacuation of the system to about  $0.001 \text{ N/m}^2$  and readout instrumentation checks are then performed. The light source is turned on, and primary and reflected

## APPENDIX

beam signals are recorded for desired wavelengths as set on the spectrograph. Normally, at least one repetition of these measurements is made.

Preparation of primary system.- The calibrated grating (step 1) is installed in the 1-m spectrograph, and the calibration lamp is mounted at the spectrograph entrance slit. The calibrated photodiode is mounted at the exit aperture and the system is evacuated for about 12 hours to an ultimate pressure of  $100 \mu\text{N}/\text{m}^2$ , after which lamp and spectrograph leak rates are checked.

Initial lamp startup.- The monitoring and readout instrumentation is checked, and the discharge lamp is purged with hydrogen for about 15 minutes at a flow rate between 10 and 20 std  $\text{cm}^3/\text{min}$ . The normal operating flow rate and internal lamp pressure are then set by valve adjustments at the hydrogen supply and at the lamp inlet.

Recording of data.- After the lamp has been on for about 20 minutes, time-integrated signal currents are recorded for desired wavelengths as set on the spectrograph. Repetitions of the measurements at various intervals over a 2- or 3-day period are made to determine data scatter.

### Description of Instrumentation and Specifications

In setting up the complete system, in addition to intensity calibrations on the lamp, consideration was given to adaptation of the lamp for use in the laboratory as a calibration tool. Regulated power supplies for the detectors and highly stable electrometers capable of measuring currents over a range of 1 pA to 10  $\mu\text{A}$  with linear analog outputs were used. An accurate integrating digital voltmeter (DVM) which measured voltage from the electrometer was used in the time integrated mode over an interval of 100 seconds. This technique of time integration of low level currents is similar to that employed by the National Bureau of Standards to calibrate photodetectors. Onsite calibration instruments for such sensitive electrometers and voltmeters were obtained and used periodically to improve the confidence level of the final measurements. In general, the instrumentation performed well and no major corrections were necessary.

The calibrated photodiode used in the lamp-intensity calibrations is extremely delicate and requires careful handling. Best results were obtained when the photodiode was mounted in a specially constructed holder and not removed. The photomultiplier detectors used in radiant-sensitivity calibrations and in the reflectance chamber were held in place by commercially available mounts.

Table II provides a detailed listing of the instruments used in this investigation. The applications and pertinent specifications are also included.



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TABLE I.- SUMMARY OF NBS PHOTODIODE SIGNAL CURRENTS

| Date                       | Current, pA, for —   |                      |                      |                      | Comments                |
|----------------------------|----------------------|----------------------|----------------------|----------------------|-------------------------|
|                            | $\lambda = 127.7$ nm | $\lambda = 158.0$ nm | $\lambda = 177.5$ nm | $\lambda = 195.0$ nm |                         |
| <sup>a</sup> 3/7/75        | 16.05                | 21.66                | 2.78                 | 2.00                 | Slight vacuum leak      |
| <sup>a</sup> 3/10/75       | 15.12                | 21.63                | 2.63                 | 1.97                 | Slight vacuum leak      |
| 3/11/75                    | 18.54                | 23.55                | 3.03                 | 2.31                 |                         |
| 3/11/75                    | 17.90                | 29.81                | 3.21                 | 2.57                 |                         |
| 3/11/75                    | 19.66                | 33.09                | 3.62                 | 2.75                 |                         |
| 3/12/75                    | 17.43                | 29.38                | 2.94                 | 2.20                 |                         |
| 3/12/75                    | 17.05                | 29.33                | 3.09                 | 2.44                 |                         |
| 3/12/75                    | 18.51                | 31.11                | 3.26                 | 2.44                 |                         |
| 3/13/75                    | 16.78                | 29.59                | 3.16                 | 2.36                 |                         |
| 3/13/75                    | 18.12                | 30.10                | 3.13                 | 2.39                 |                         |
| 3/21/75                    | 20.08                | 35.84                | 3.79                 | 2.88                 |                         |
| 3/21/75                    | 18.52                | 32.73                | 3.38                 | 2.73                 |                         |
| 3/28/75                    | 15.45                | 27.06                | 2.80                 | 2.12                 |                         |
| 3/28/75                    | 16.45                | 28.59                | 2.88                 | 2.06                 |                         |
| 4/16/75                    | 16.57                | 28.21                | 3.15                 | 2.10                 |                         |
| 4/17/75                    | 16.26                | 29.29                | 2.89                 | 2.14                 | New capillary installed |
| Average                    | 17.60                | 30.39                | 3.18                 | 2.40                 |                         |
| Standard deviation         | $\pm 1.31$           | $\pm 2.27$           | $\pm 2.28$           | $\pm 2.26$           |                         |
| Percent standard deviation | 7.43                 | 7.46                 | 8.78                 | 10.85                |                         |

<sup>a</sup>These measurements not included in average signal calculation.

TABLE II.- INSTRUMENTATION AND PERTINENT SPECIFICATIONS  
FOR LAMP CALIBRATION SYSTEM

| Instrument                               | Function   | Critical specifications   |
|--|--|---|
| Monochromator                            | Measurement of absolute intensity of lamp  | 1-m concave grating, 1200 lines/mm, 120-nm blaze wavelength, $4^{\circ}8'$ blaze angle, $\text{MgF}_2$ coated, 0.83-nm/mm dispersion  |
| Monochromator                            | Monochromatic light source for reflectance chamber grating-efficiency measurements | 1/2-m Seya type, 600 lines/mm concave grating, blaze wavelength 80 nm, blaze angle $2^{\circ}35'$ , $\text{MgF}_2$ coated, 3.4-nm/mm dispersion   |
| Electronic photo-detector readout system | Reflectance chamber output measurements  | <p><u>Power supply:</u> -500 to -2500 V dc, 0 to 1 mA, 0.05-percent stability (1 day)</p> <p><u>Electrometer:</u> <math>10^{-3}</math> to <math>10^{-11}</math> ampere, 1-percent accuracy on all ranges, 0.5-percent stability (1 day)</p> <p><u>Strip chart recorder:</u> -0.5 mV to 10.5 mV dc</p> |
| Vacuum ultraviolet light source          | Calibrated for absolute intensity in present study                                 | 1000 watts continuous 8000 watts intermittent (other specifications described in text)  |
| Power supply                             | dc supply for calibrated vacuum ultraviolet light source                           | 200 to 2000 V dc, 100 to 500 mA, current regulation 0.25 percent for normal changes in lamp operating conditions  |
| Pumping system                           | Reflectance chamber evacuation   | <p><u>Mechanical pump:</u> 2.36 liter/s</p> <p><u>Diffusion pump:</u> 85 liter/s</p> <p><u>Cold trap:</u> 0.8 liter capacity</p> <p><u>Ultimate vacuum:</u> <math>10^{-4}</math> N/m<sup>2</sup></p>  |
| Mechanical pump                          | Calibration lamp evacuation  | 2.36 liters/sec pumping speed   |
| Liquid flowmeter                         | Calibration lamp water flow regulation   | 0 to 1100 cm <sup>3</sup> /min, 5-percent accuracy  |

TABLE II.- Concluded

| Instrument                    | Function  | Critical specifications   |
|-------------------------------|---|---|
| Gas flowmeter                 | Hydrogen flow-rate measurement for lamp calibration                   | Calibrated for hydrogen, 0 to 5 V dc output, 1-percent accuracy, 0.5-percent repeatability, 0 to 50 cm <sup>3</sup> /min            |
| Pressure meter                | Gas pressure measurement in lamp calibration                          | 7.5 to 7500 N/m <sup>2</sup> , 0 to 5 V dc output, 0.03-percent accuracy, 0.01-percent linearity, 0.01-percent stability (1 day)    |
| Electrometer                  | Current measurement, calibrated photodiode output                     | 10 <sup>-14</sup> to 0.3 ampere, 2-percent accuracy, noise level $3 \times 10^{-15}$ ampere, 0 to 5 V dc output, drift 1 mV (24 hr) |
| Picoampere current source     | Electrometer calibration check  | 10 <sup>-14</sup> to 10 <sup>-4</sup> ampere output, 1-percent accuracy, 0.15-percent stability (1 month)                           |
| Integrating digital voltmeter | Electrometer output measurements                                      | 0.1 to 1000 V full scale, 0.01-percent accuracy (1 digit), stability 0.006 percent (6 month)  |
| Digital voltmeters            | Gas flow-rate meter and pressure meter output measurements            | 0.1 to 1000 V dc<br>0.05-percent accuracy (1 digit),<br>0.01-percent linearity<br>0.05-percent stability (3 month)                  |
| dc power supply               | Power for calibrated photodiode                                       | 0 to 320 V dc, 1.5 amperes max., load regulation 0.01-percent, ripple 0.5 mV rms, stability 0.05 percent                            |
| dc power supply               | High-voltage supply for sodium salicylate coated photomultiplier      | 500 to 6010 V dc, 0 to 20 mA, 0.01-percent regulation to full load, ripple 5 mV rms, stability 0.005 percent (1 hr)                 |
| Strip chart recorder          | Photomultiplier output on 1-m monochromator (used for spectrum scans) | 5 mV to 100 V dc full scale, accuracy 0.2 percent full scale, stability 0.1 percent full scale                                      |

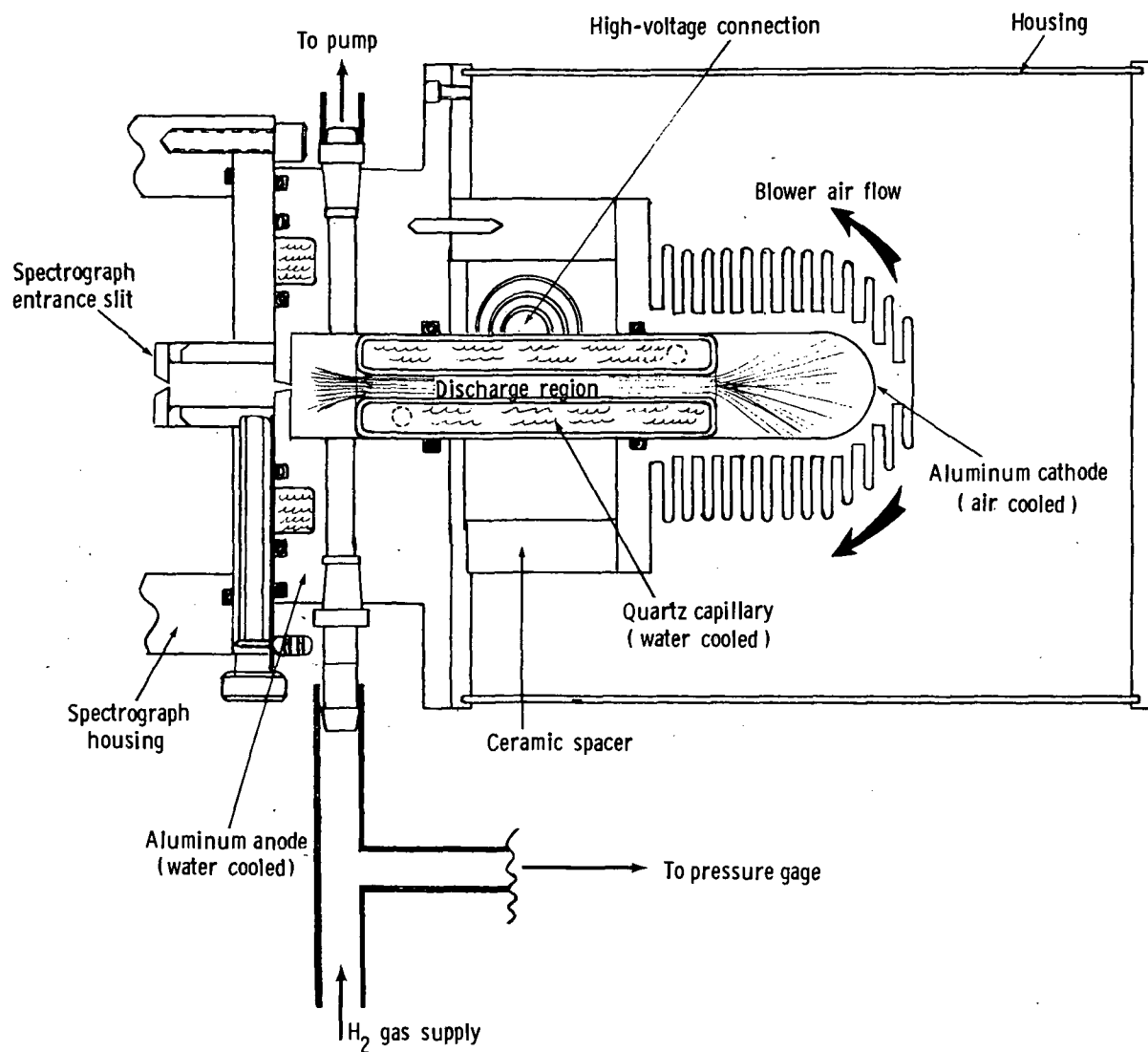
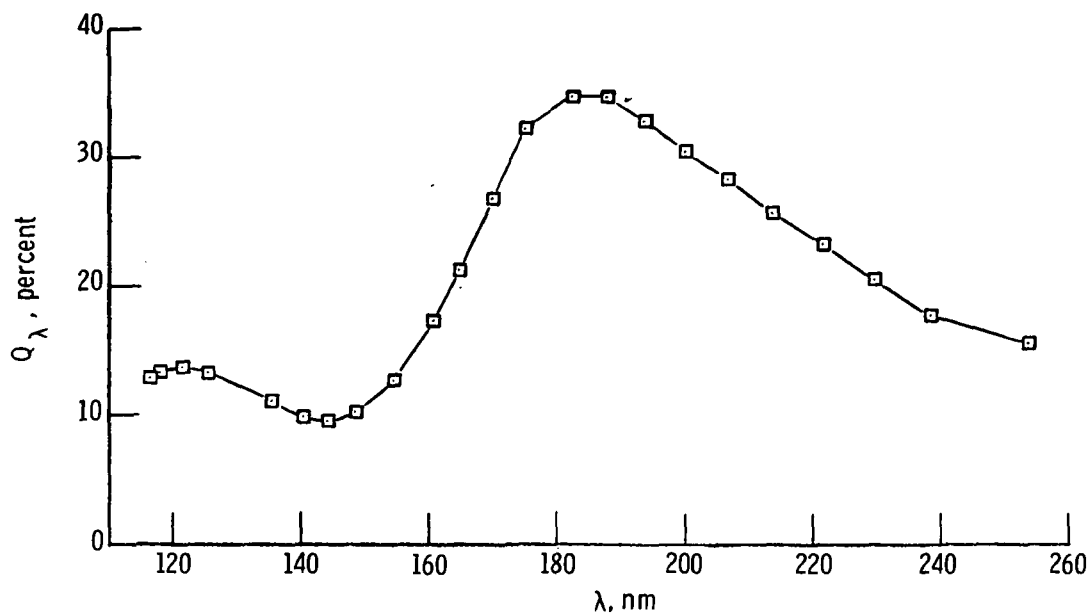
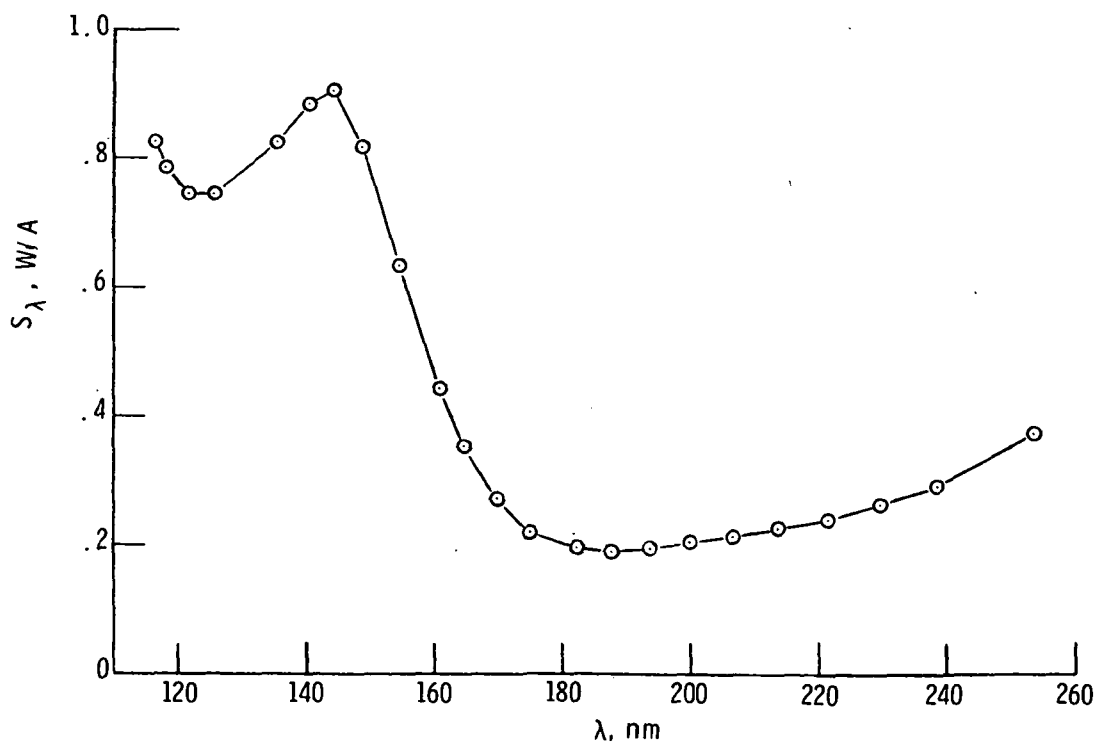


Figure 1.- Diagram of lamp configuration as attached to spectrograph.



(a) Quantum efficiency.



(b) Radiant sensitivity.

Figure 2.- Properties of NBS calibrated photodiode.

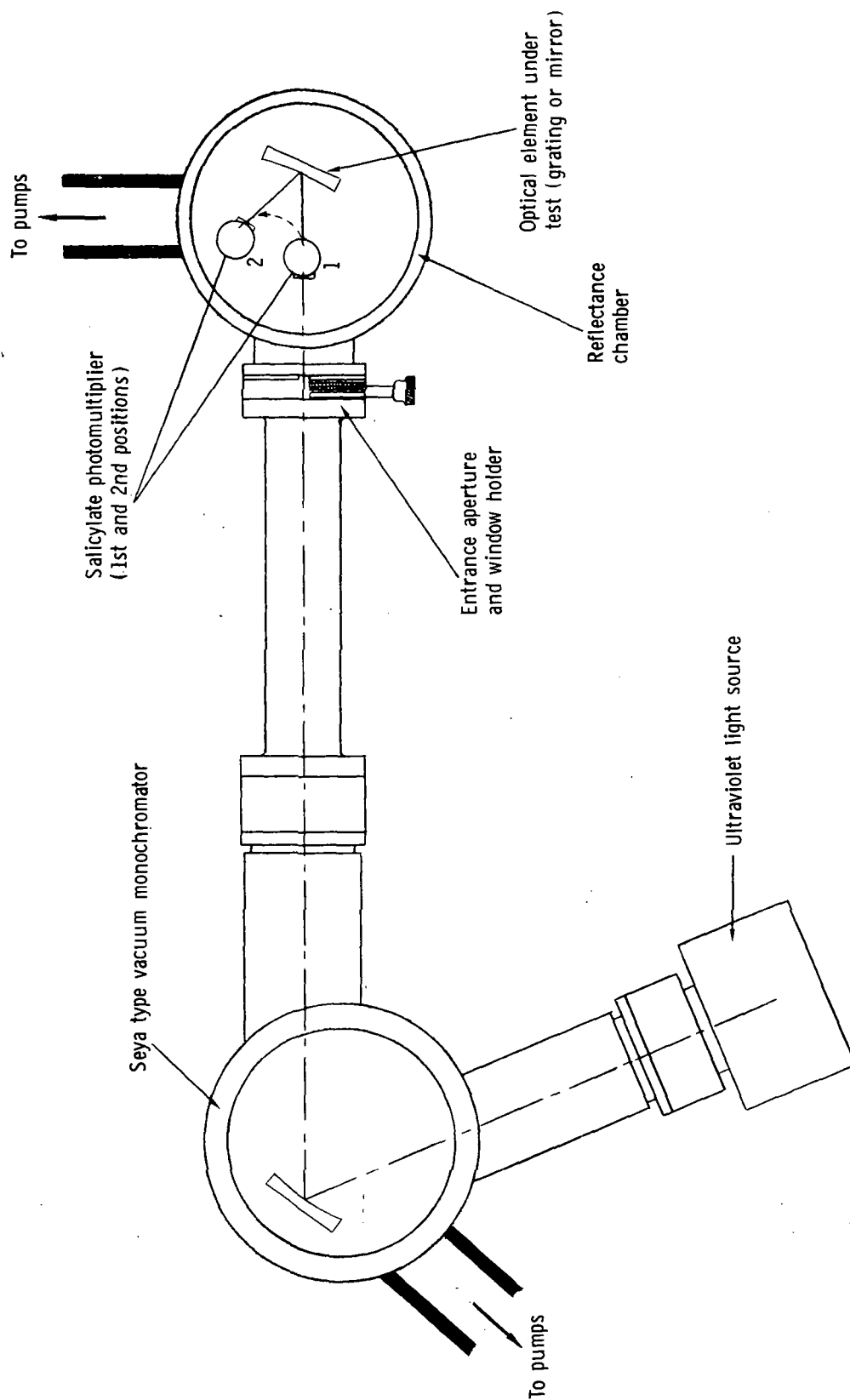
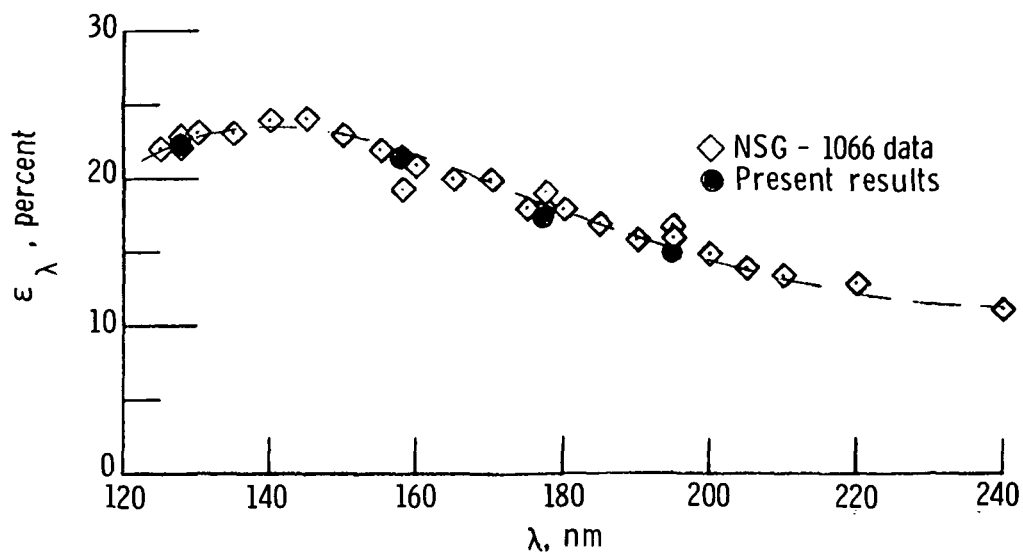
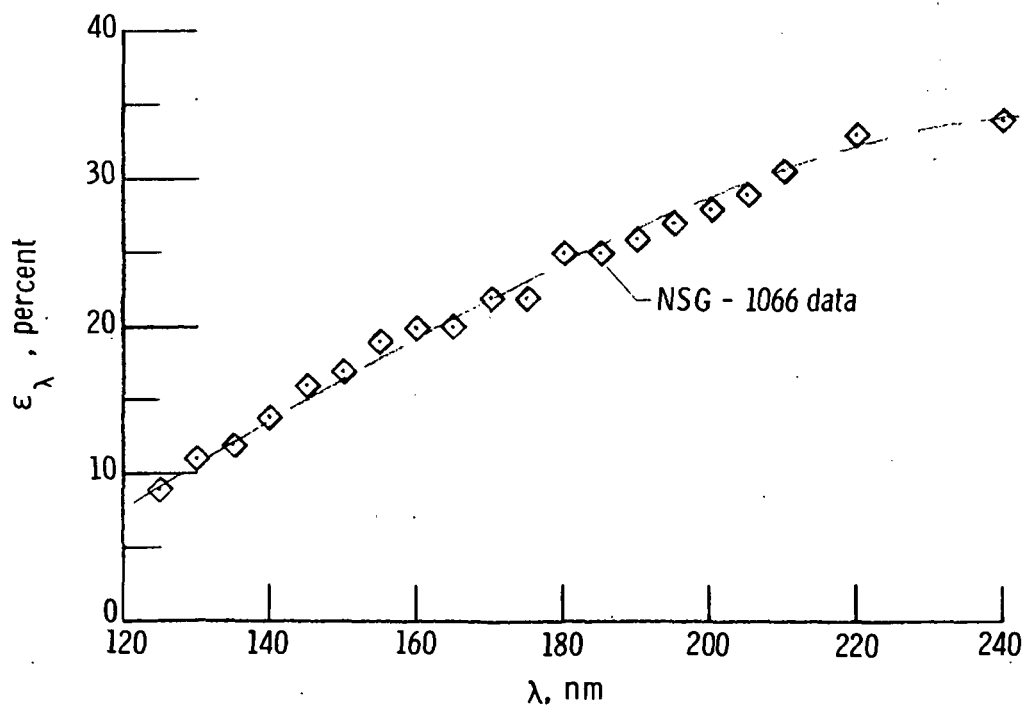


Figure 3.- Top view of reflectance chamber attached to Seya spectrograph.





(a) First-order grating efficiency.



(b) Zero-order grating efficiency.

Figure 4.- Measured grating efficiencies, zero and first order.

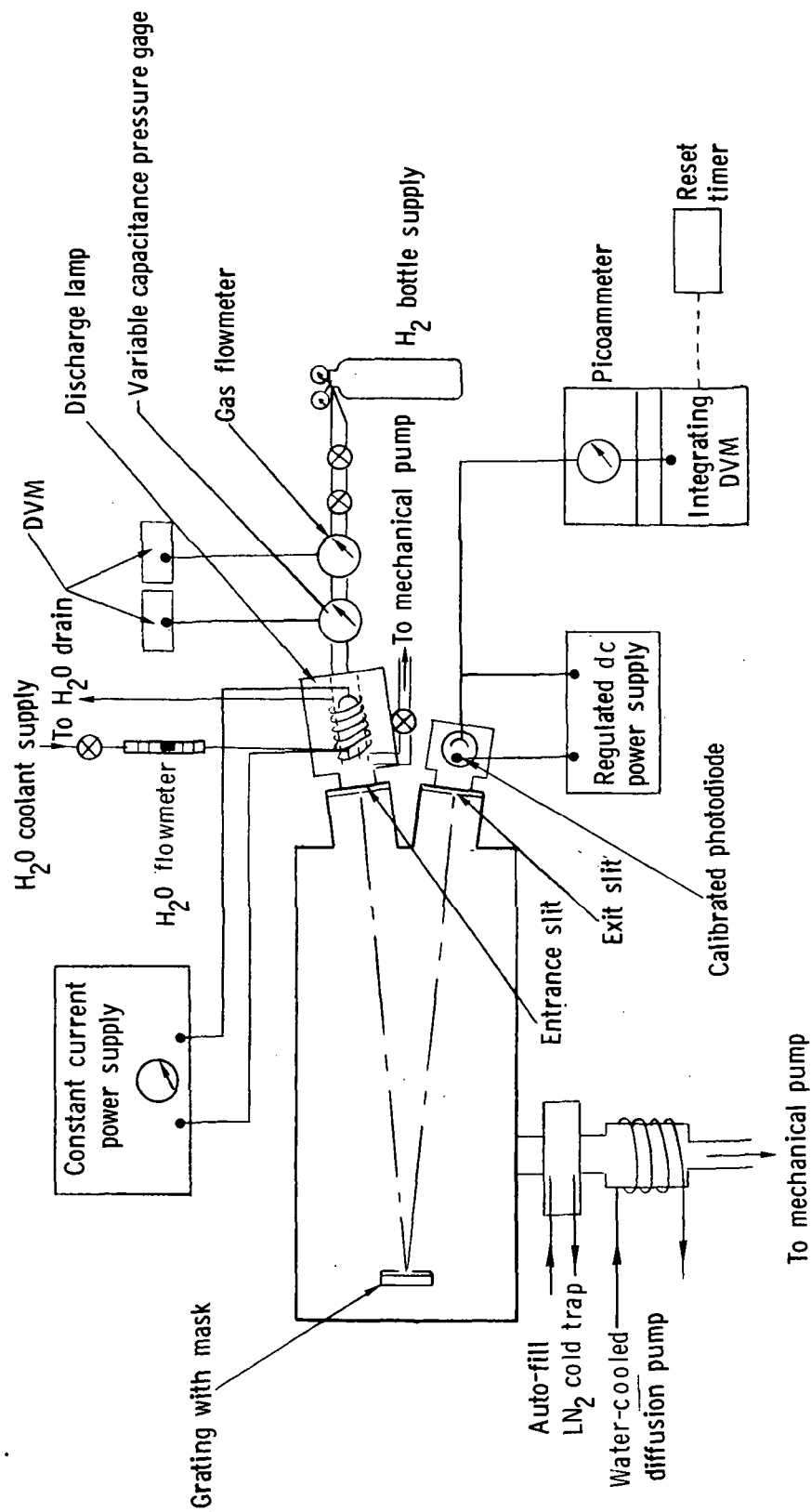


Figure 5.- Diagram of 1-m spectrograph with hydrogen discharge lamp and peripheral equipment in operation position.

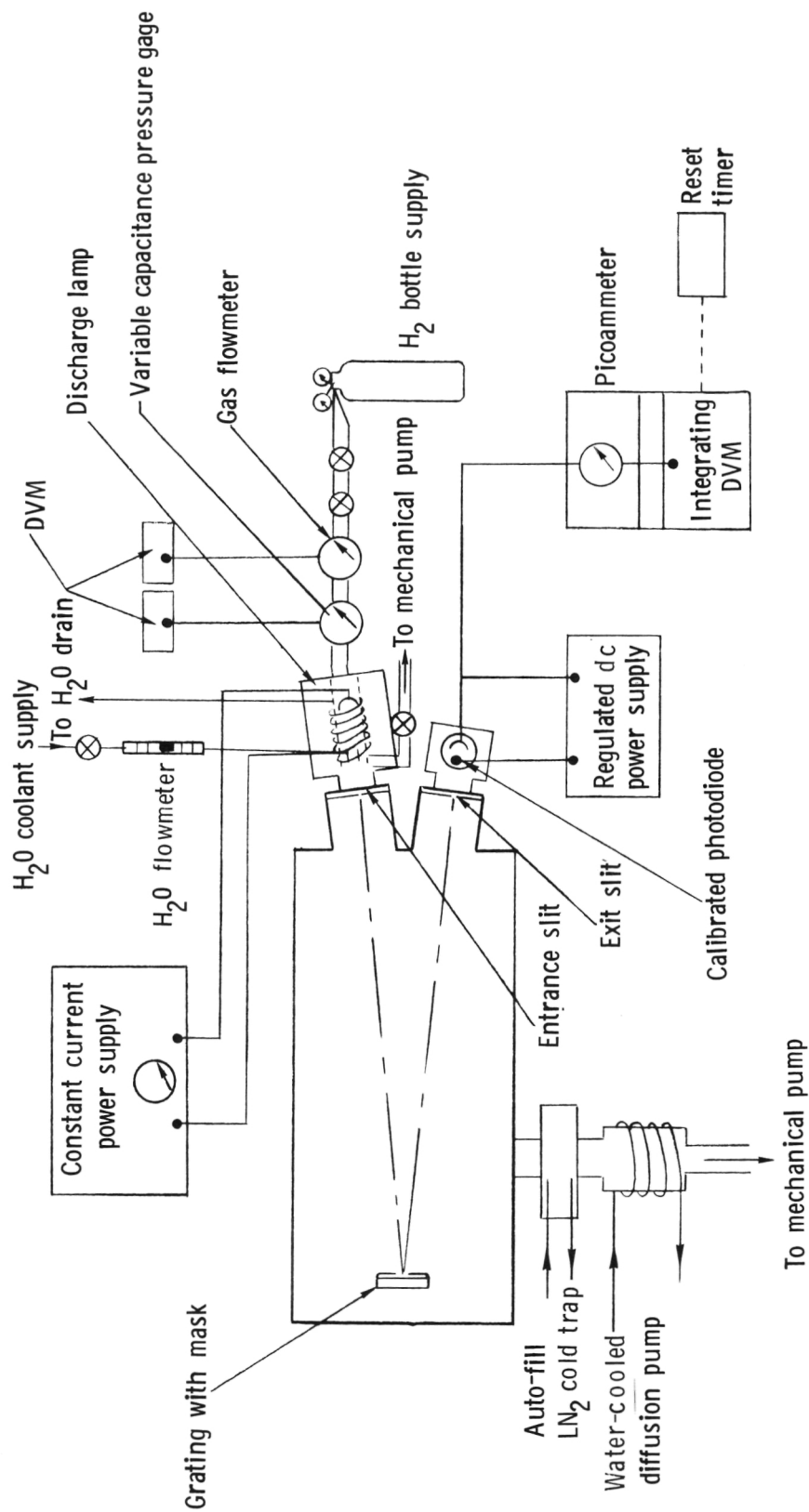
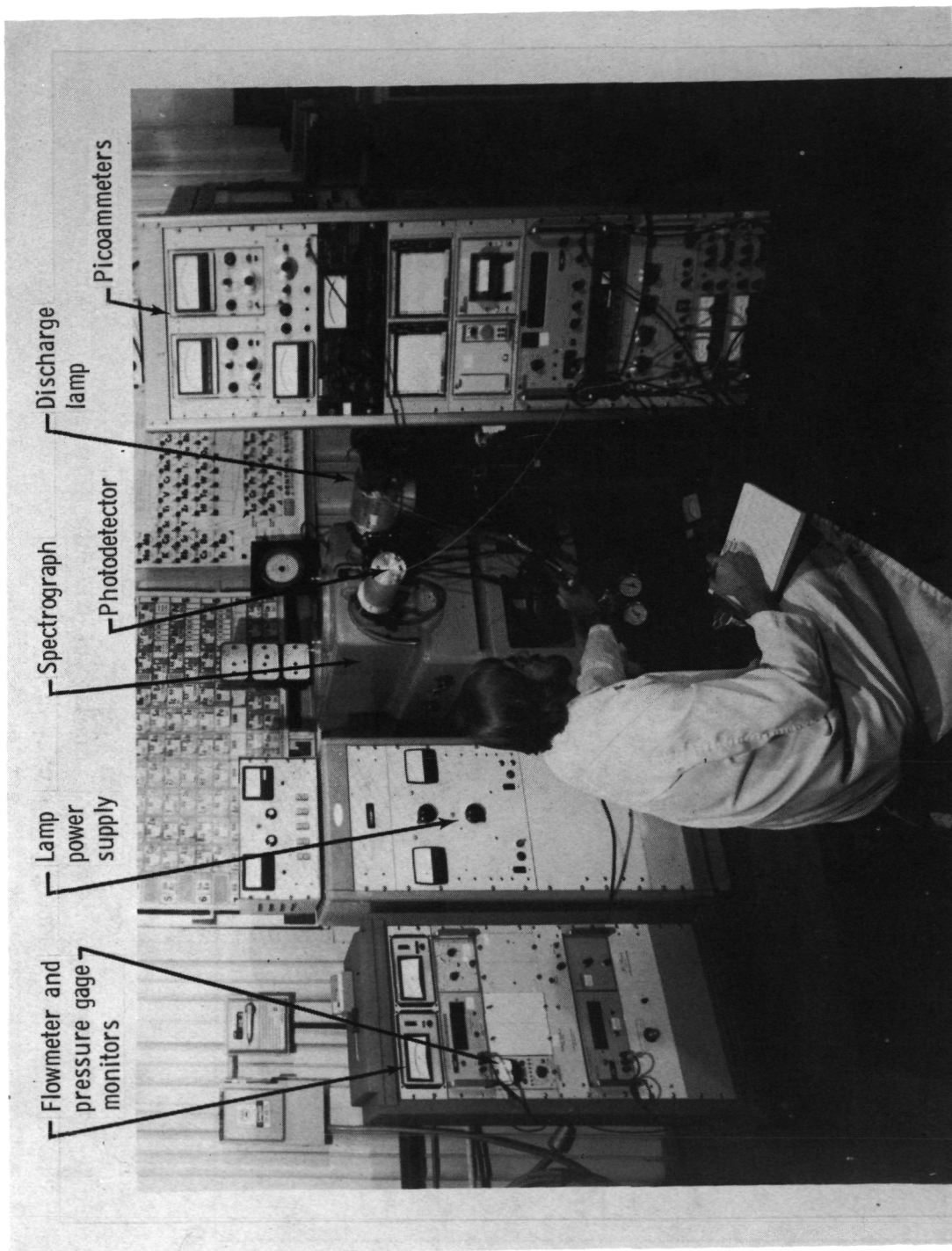


Figure 5.- Diagram of 1-m spectrograph with hydrogen discharge lamp and peripheral equipment in operation position.



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Figure 6.- Photograph of 1-m calibration spectrograph with lamp in operation.

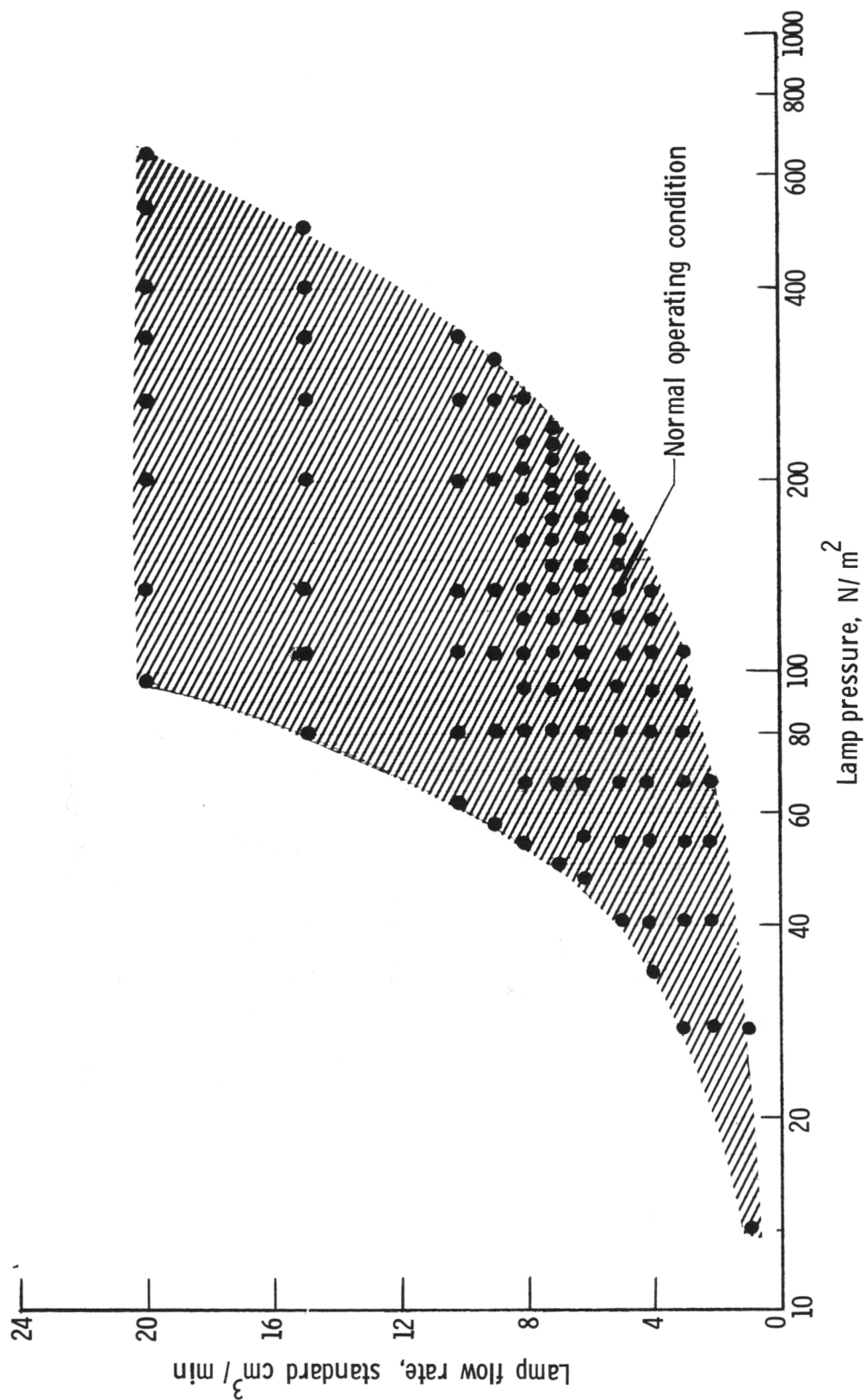


Figure 7.- Map of hydrogen flow rate as function of pressure illustrating present operating conditions of discharge lamp used in determining lamp characteristics.

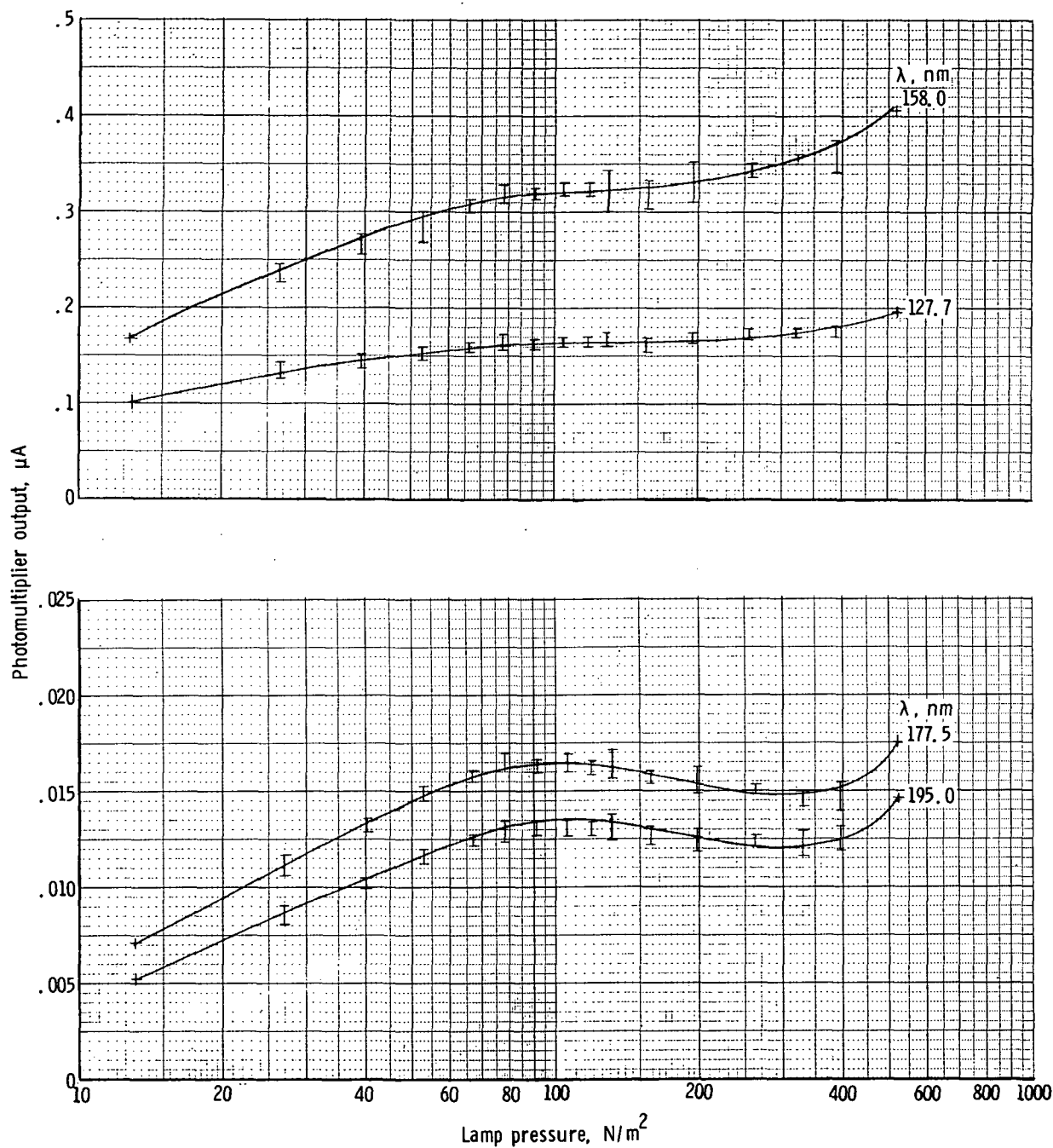


Figure 8.- Variation of lamp intensity with hydrogen pressure at selected wavelengths.

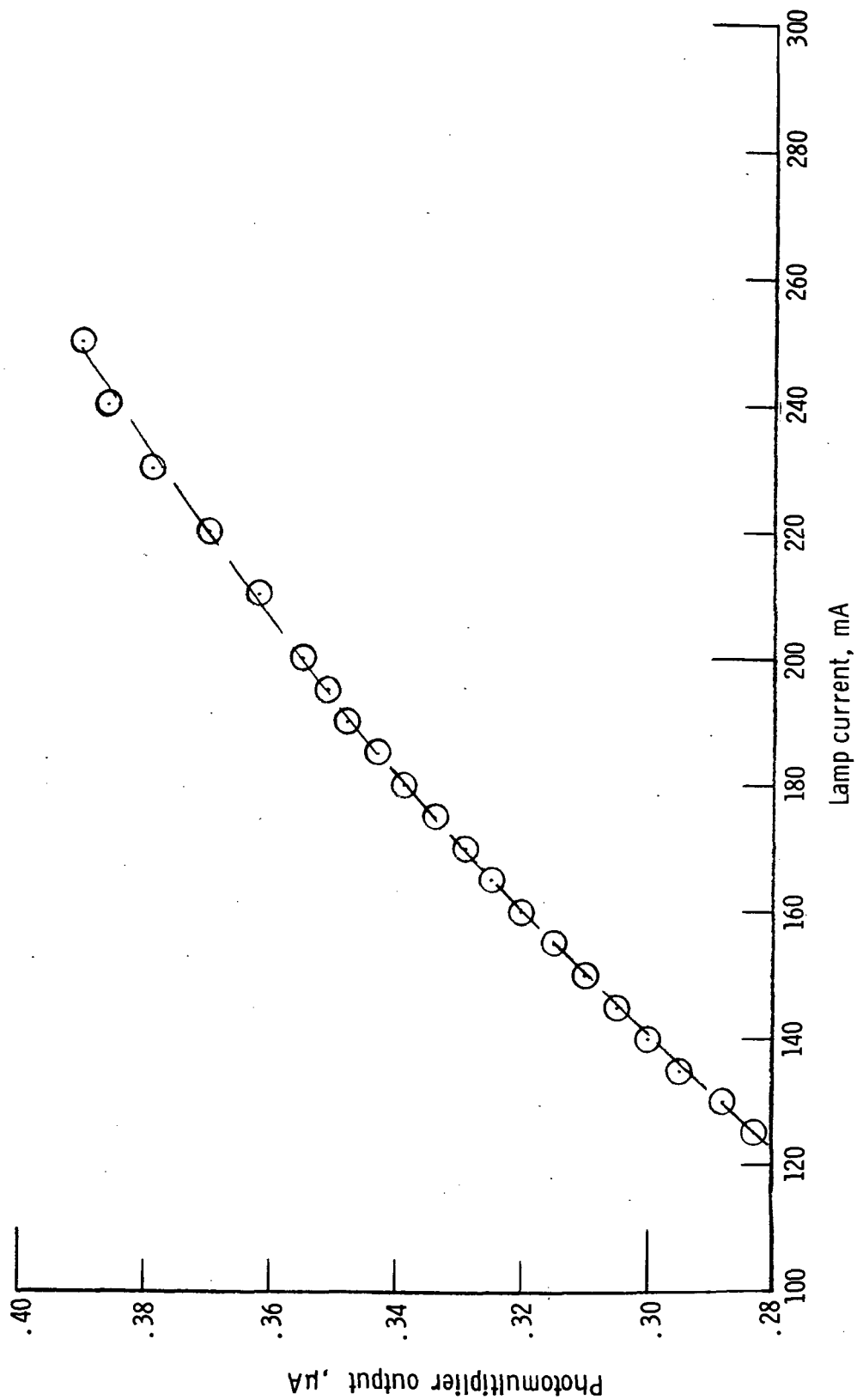


Figure 9.- Variation of lamp intensity with lamp current for wavelength of 158 nm.

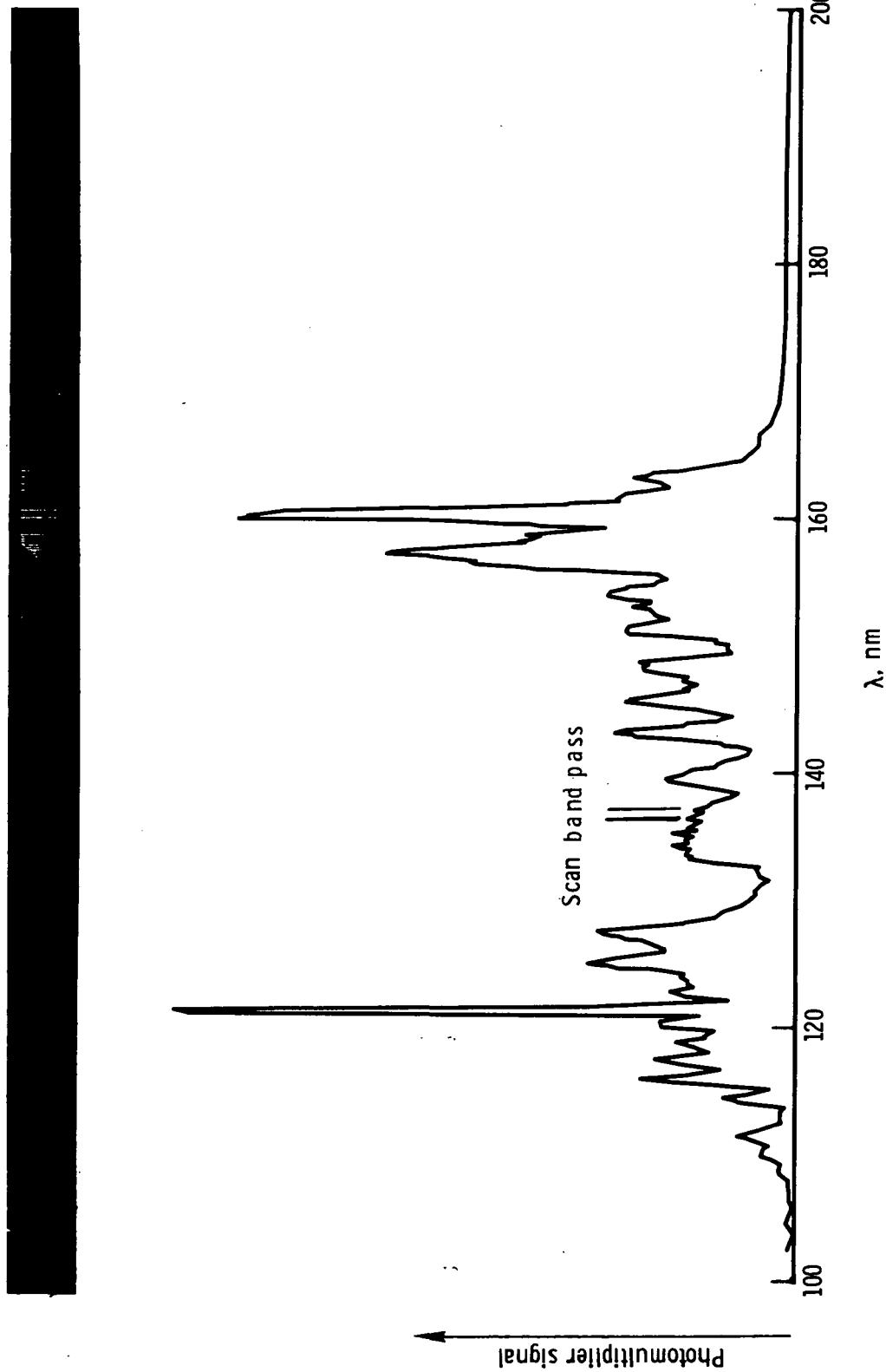


Figure 10.- Photograph of spectrum and scan of hydrogen discharge lamp.



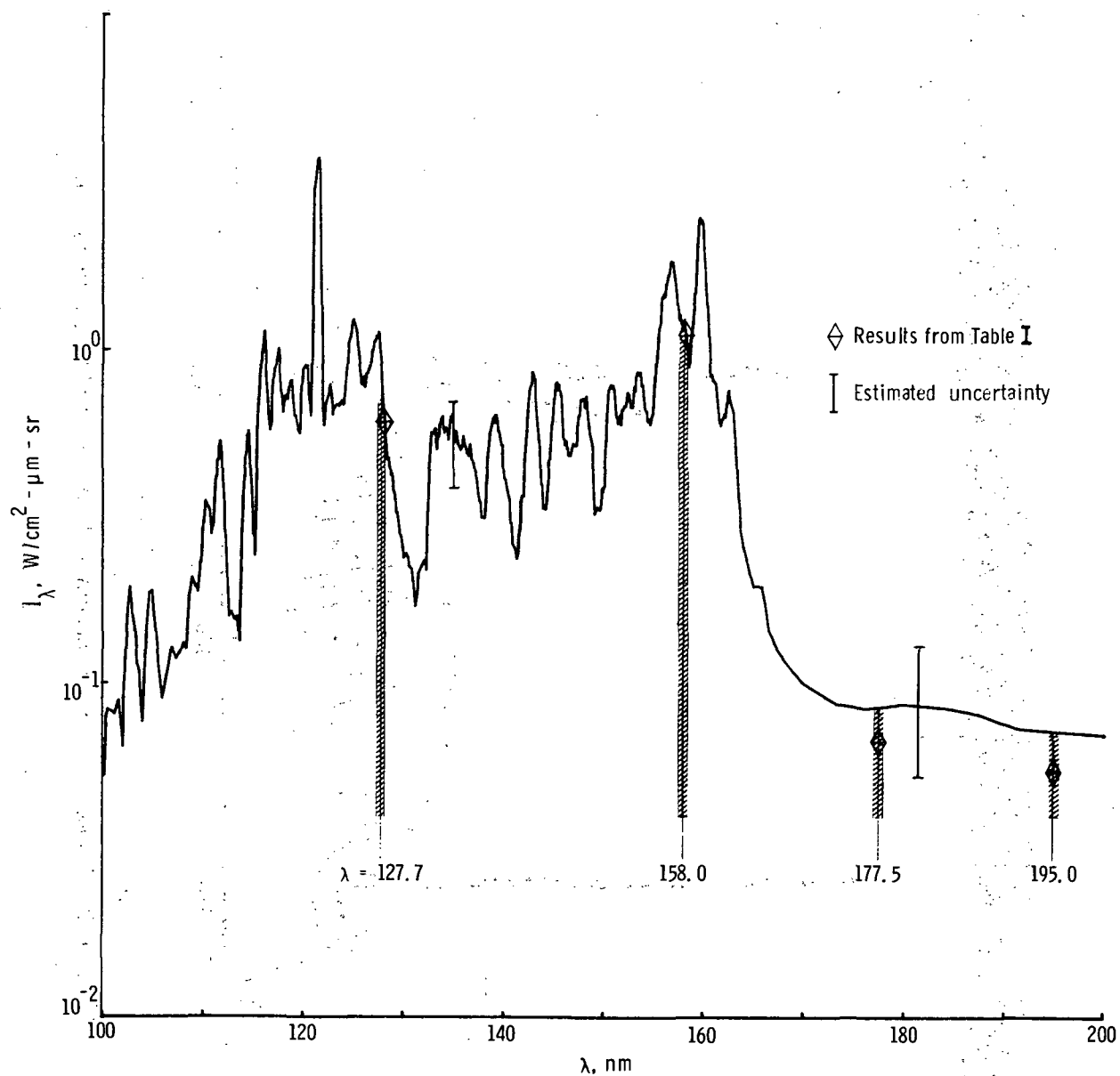


Figure 11.- Radiance of hydrogen lamp determined from spectral scan.

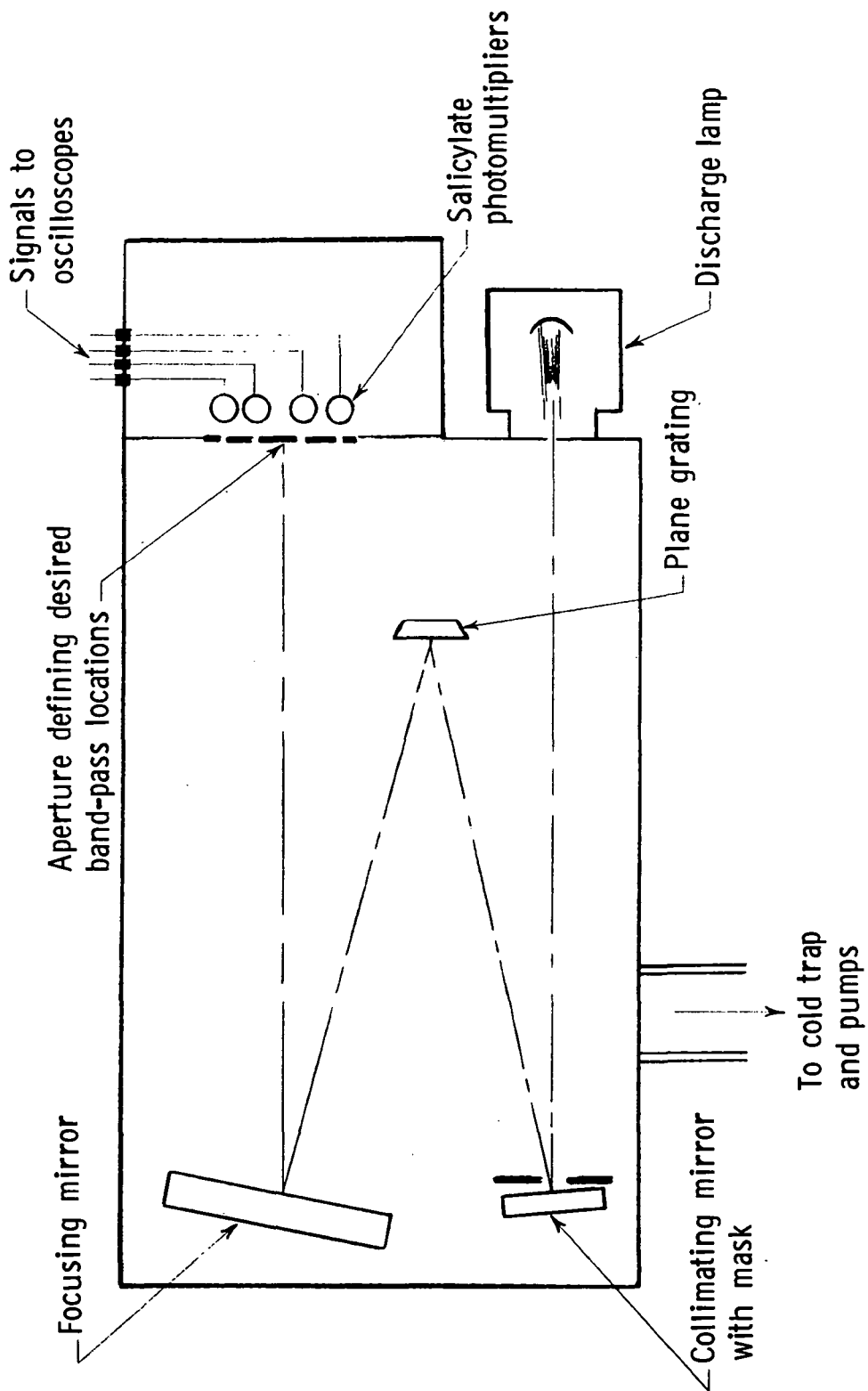


Figure 12.- Diagram of lamp in use as calibration source for three-surface vacuum polychromator.



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